The Terminator Tether™ Satellite Disposal Device

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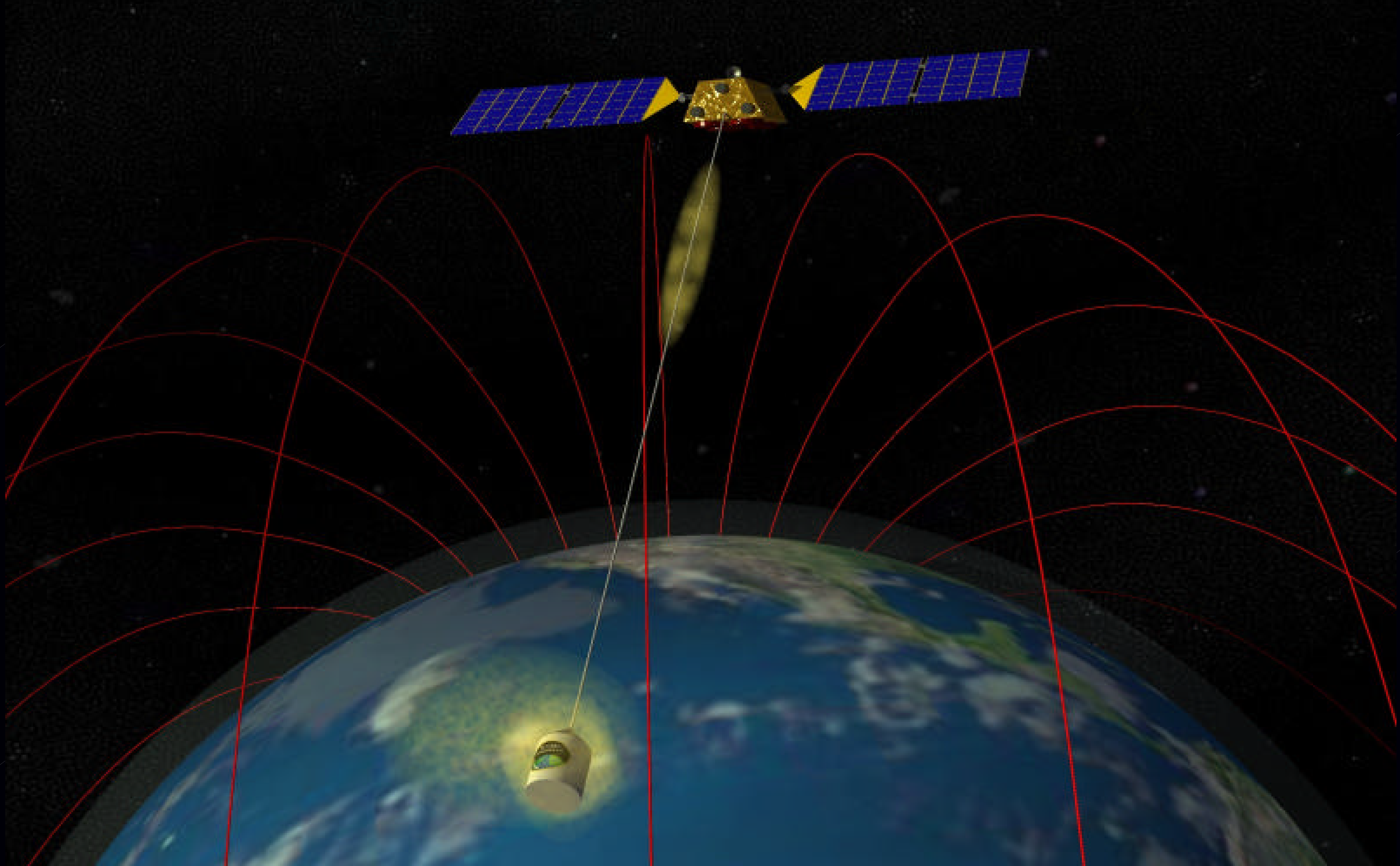


The Terminator Tether™ Device for Mitigation of Debris Growth

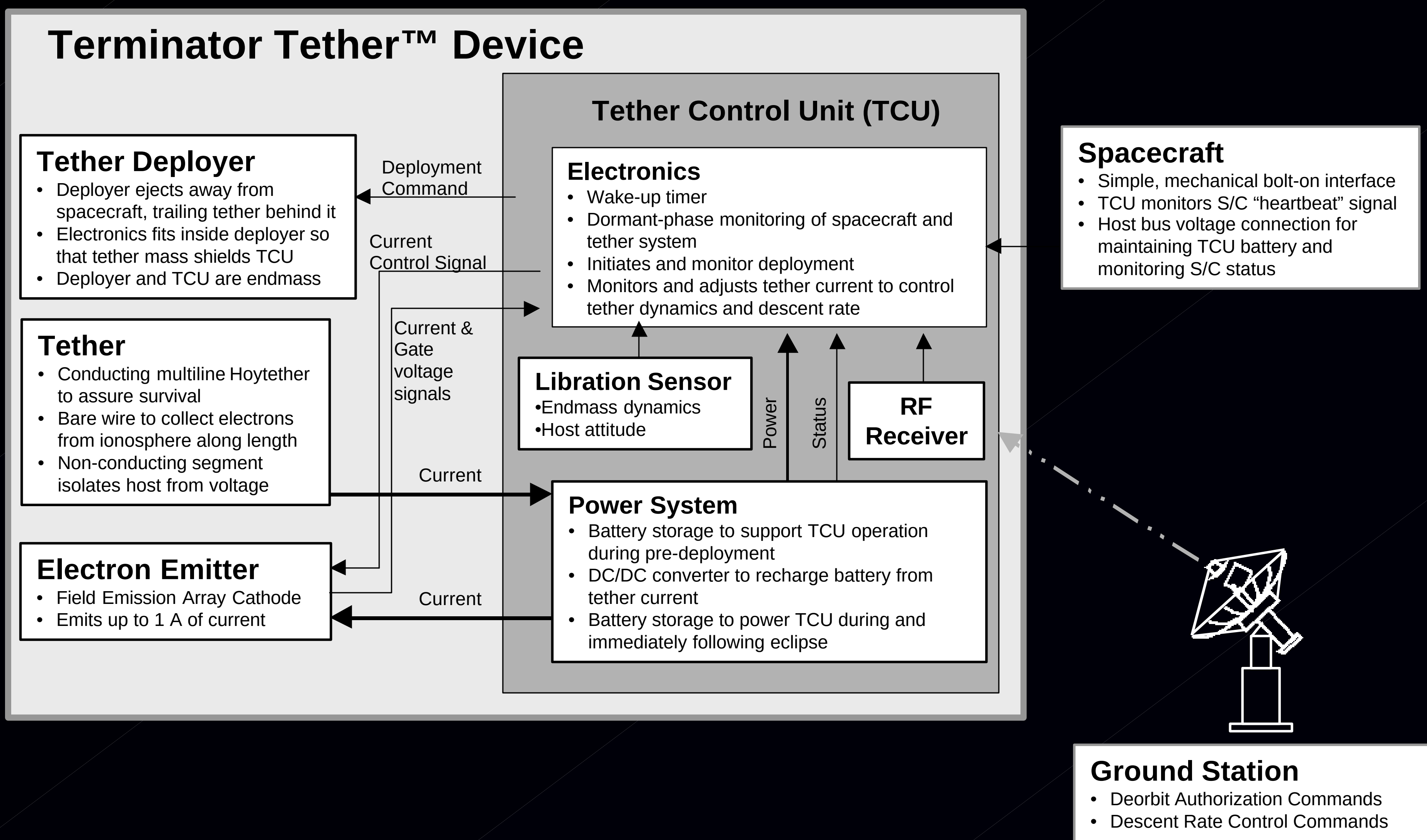
- Masses < 2% of host mass
- Dormant during normal satellite operation
- Deploys tether when satellite dies or is obsolete
- Tether drags against Earth's magnetic field
- Deorbits satellite in weeks
- No propellant required
- Self-powered — needs no input power
- Can deorbit a dead satellite

Initial Development Funded by $670K in NASA/MSFC SBIR Contracts

Phase II Design Approach

- Commercial customers want zero cost, mass & hassle
- Terminator Tether™ design choices made primarily to minimize cost, mass, and satellite integration issues
- Phase II effort building breadboard-level prototypes to demonstrate feasibility of key systems & capabilities
  - Deployer mechanism for survivable conducting tether
  - Sized for Iridium class spacecraft (>1000 kg)
  - Ruggedized Field Emission Array Cathodes (FEAC)
  - Tether libration state sensor
- Issues left for future work
  - Hardware-In-Loop test capability
  - Radiation-hard electronics
  - Detailed gas-ejector plumbing design
  - Uplink communications system

Terminator Tether™ Functional Block Diagram

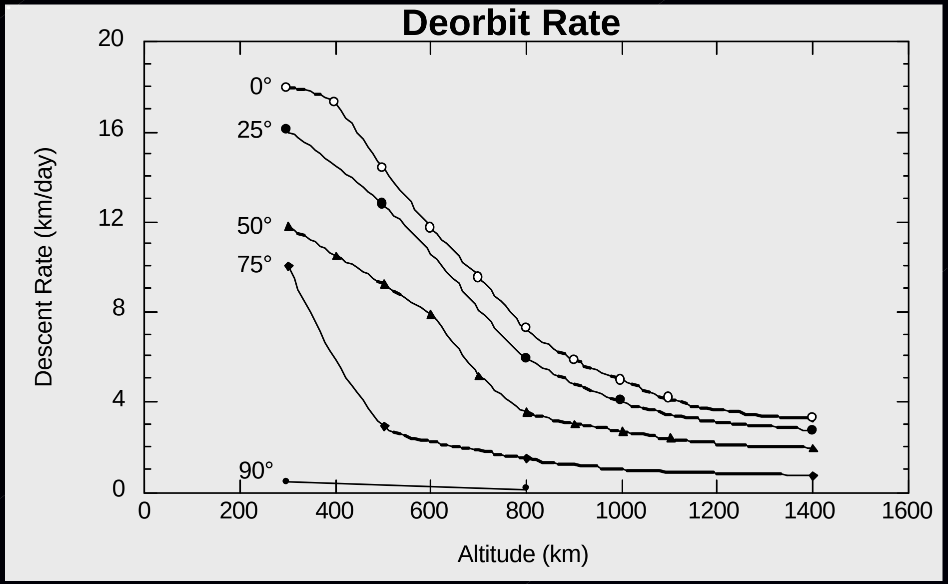


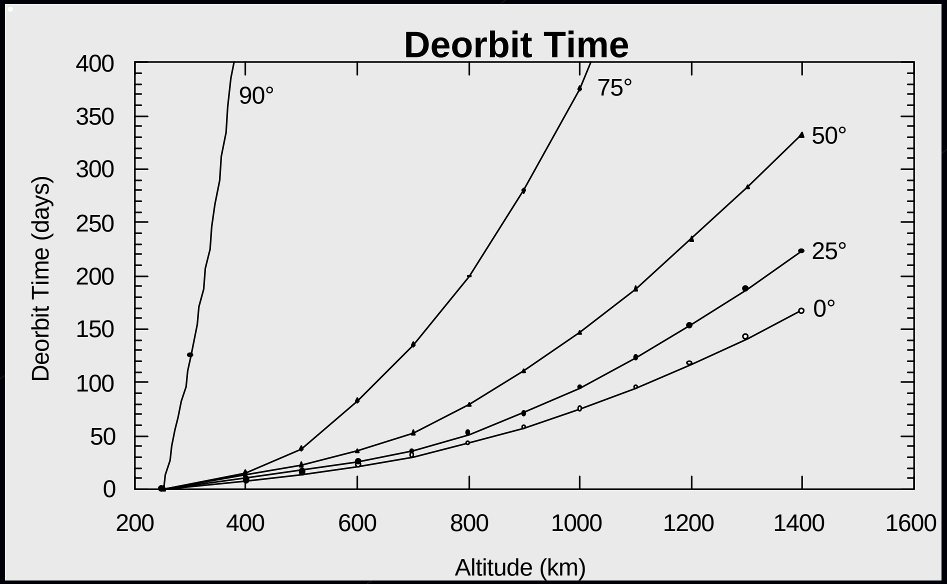
Terminator Tether™ Deorbit Performance

- Deorbit performance of 7.5 km tether with mass 1% of host spacecraft mass
- Can reduce tether length and mass if longer deorbit times are acceptable
- Deorbit rate strongly depends on inclination
- Most useful for Low Earth Orbits (<2200 km)

Examples: (tether mass = 1% of host mass)

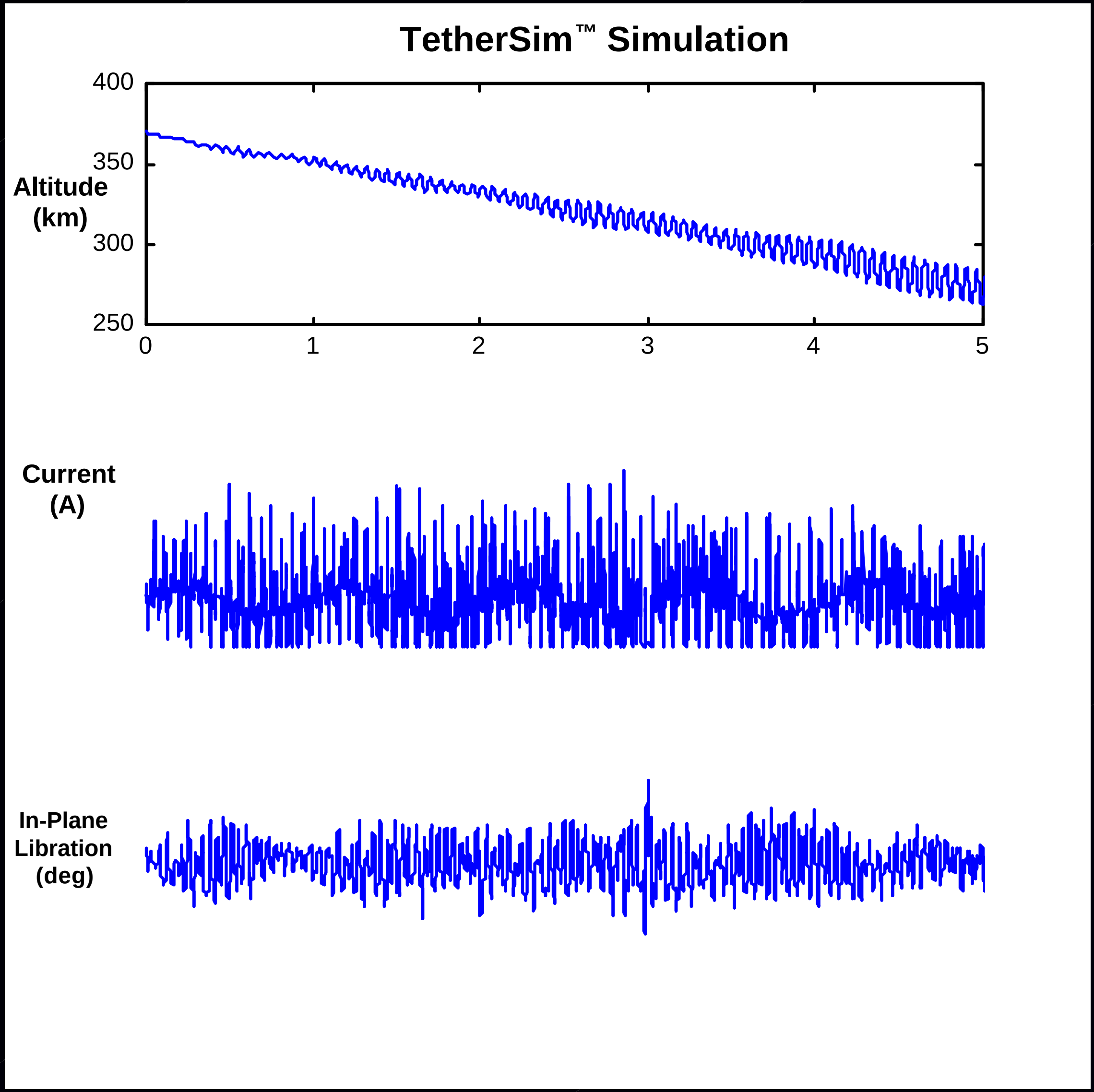
- Upper Stage, 400 km, 50°: 14 days
- Satellite, 850 km, 50°: 3 months
- Satellite, 1400 km, 50°: 11 months





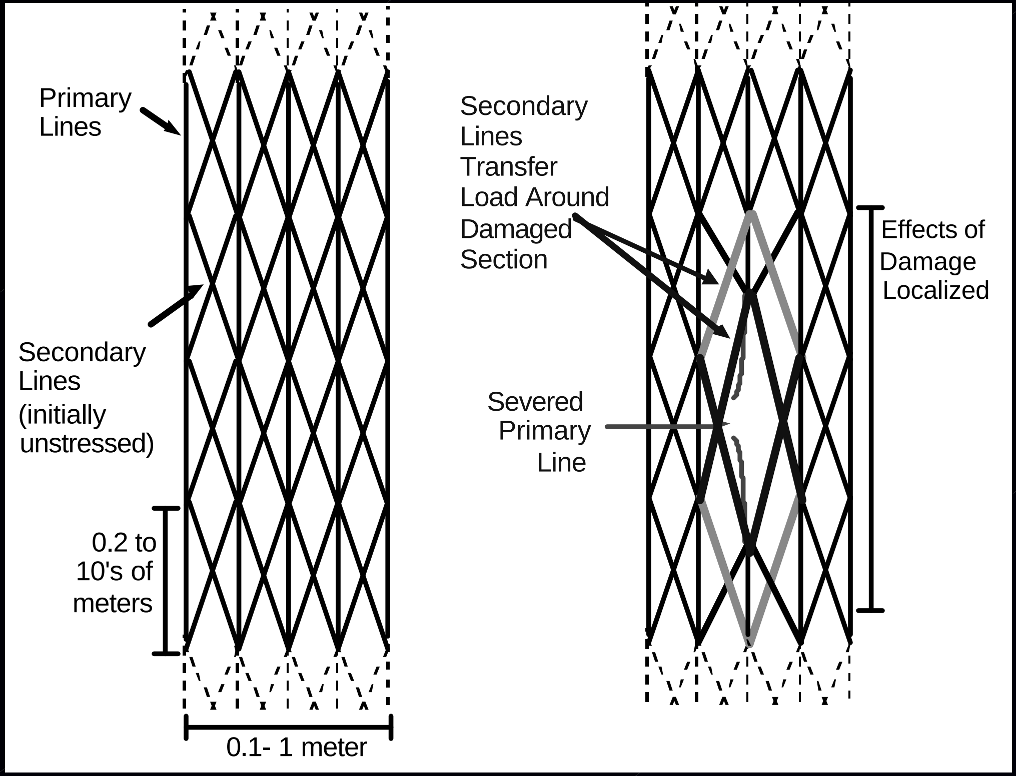
Terminator Tether™ Performance for Deorbit of a MightySat

- Simulation of 1.25 kg, 5 km long tether with 2.25 kg endmass
- Deorbits 125 kg satellite from a 370 km, 51° orbit
- Descent rate: 22 km/day
- Re-entry in ~1 week
- Feedback algorithm stabilizes tether dynamics
- Orbit becomes slightly elliptical from day/night variations in ionospheric density

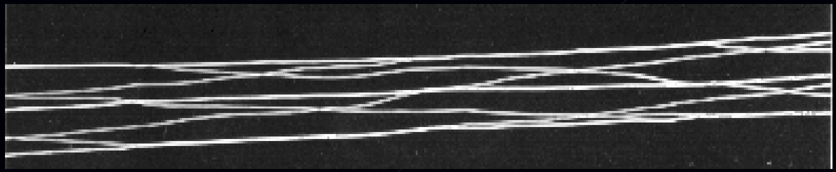


Survivable Conducting Tether

- TT™ uses Hoytether™
  - Interconnected Multistrand
  - >99% Survival Probability
  - Decades-Long Lifetime
  - Patent Pending Design

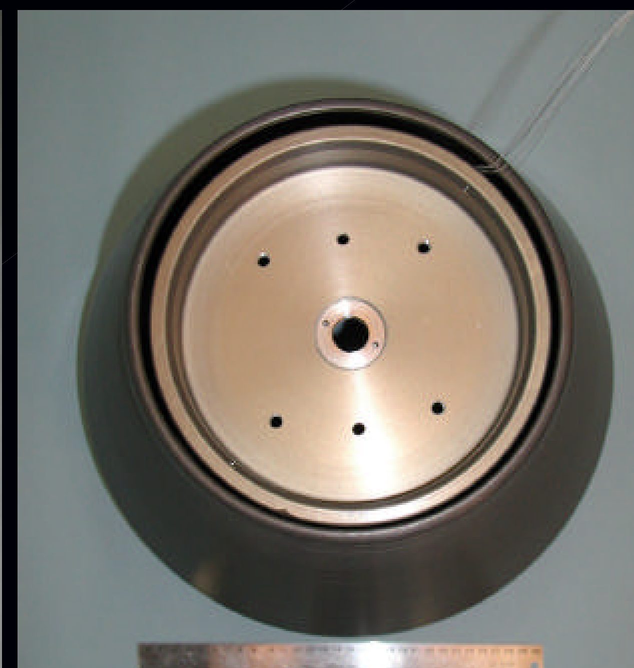


Hi-Gee “Pirn” Winding



Terminator Tether™ Deployer

- Deployed downwards -- Deployer is endmass
  - Gets tether below constellation
  - Allows electrical isolation of satellite
- Tether pays off end of "pirn" wound spool
- Electronics fit inside spool - shielded by tether
- Tether capsule ejected by gas piston action
- No active brake – braking achieved by adhesive on last section of tether



Tether Deployment Mechanism

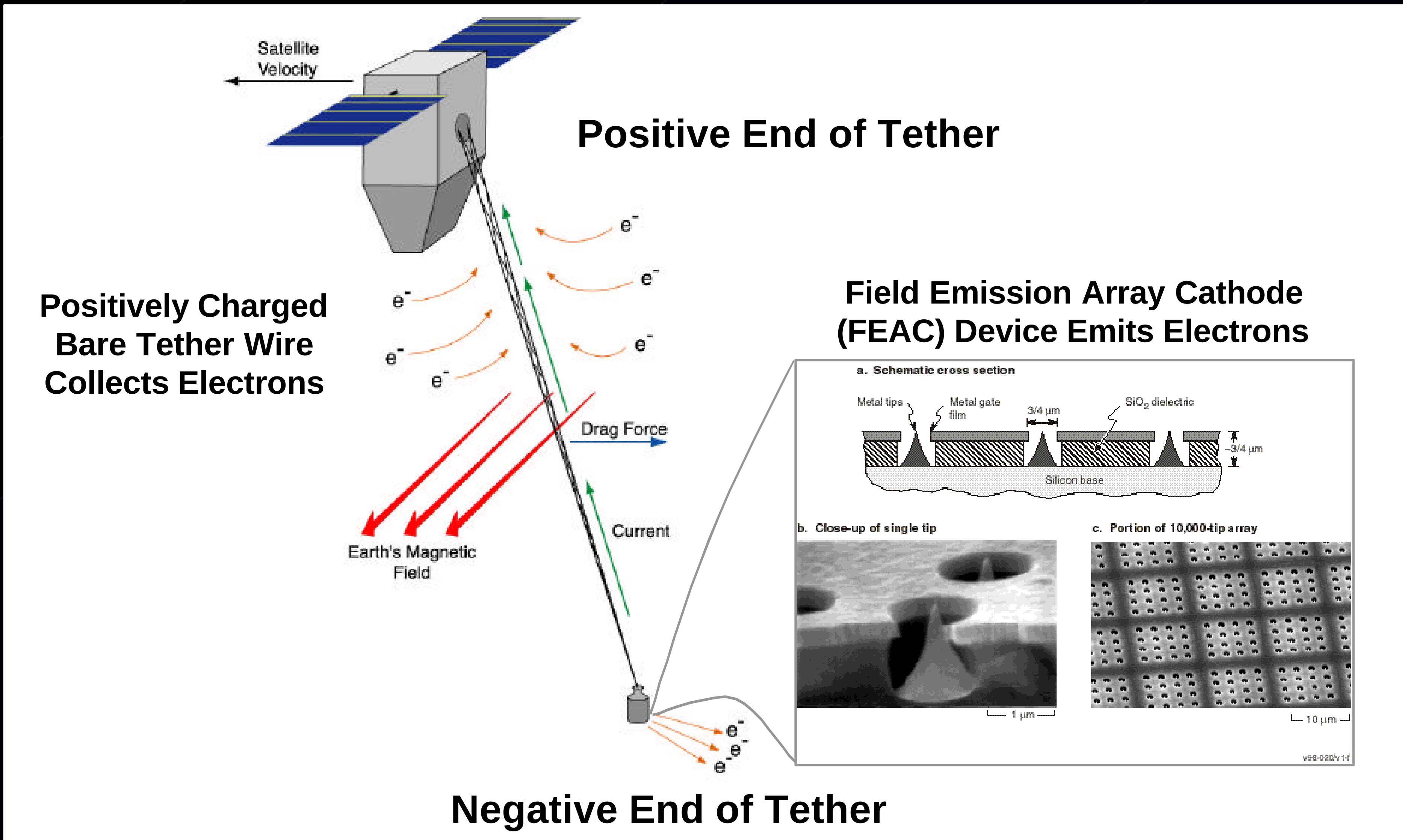
- **Primex Aerospace subcontractor**
  - **Ejection mechanism**
  - **Canister fabrication**
- **Tether canister secured to ejector/mount by ball lock**
- **Cold-gas piston ejects canister below spacecraft at 2-3 m/s**
- **No compressed springs**
- **Fast, torque-free ejection**
- **Conducted "Quick & Dirty" deployment test**
- **Need further testing to measure deployment tension and verify passive braking method**

Tether Control Unit Fabrication & Fit

- Prototype Electronics Purchased
  - CMOS Digital Cameras
  - 68332 based Flight Computer (Rad-Hard Versions Available)
  - 68HC11 Kalman Filter Processor
  - 2000 mA-hr NiCad Batteries
  - DC/DC Battery Charge Converters
  - DC/DC High Voltage Converters
  - High Voltage Vacuum Relays
- Assembling Into Circuit for Test
- Fitting Circuit on Mock Support Core
- Mass/Volume Mockup Components
  - Power Processor for FEAC/Contactor
  - EPL 250 Plasma Contactor (alternate)
  - Tank with 1 kg Xenon (optional)
  - 2-Way FM Radio (2 W)
  - Lithium Primary Battery
- Significant Volume Still Available

Mechanical-Thermal Support Core
Fits Inside Tether Spool

Field Emission Array Cathodes (FEAC)



Field Emission Array Cathode: Low-Power Electron Emitter

- Plasma contactors require gas feed and large warm-up power
- TT™ will use Field Emission Array Cathode (FEAC)
- Microtips emit electrons at low applied voltage (~75 V)
- Requires no propellant and very low power consumption
- Enables control of tether current
- FEAC Device must be designed to overcome space-charge limitations on current density
- FEAC Device must be ruggedized to operate in LEO environment

- Joint TUI/MSFC/JPL/U. Michigan/SRI/LRI/NRL effort to develop and test ruggedized FEACs:
  - TUI leading effort to fabricate FEACs coated with ZrC
  - JPL & U. Michigan will perform environmental tests
  - Ruggedized FEACs will also be useful for Hall & Ion thrusters

FEAC Ruggedization & Testing

- Using existing design for 50K tip Mo FEA devices
  - 2 μm fabrication process
  - 60-120 V typical operating voltages
- Effort focusing on studying effect of ZrC coating on FEAC performance in Oxygen and Xenon environments
- NOTE: ZrC *might* provide some resistance to sputtering, but smaller tips, lower voltage devices are a more promising solution for this issue

- TUI procuring: STATUS
  - 20 uncoated Mo FEACs — DELIVERED to JPL, U.Mich., LRI
  - 12 ZrC coated FEACs from LRI: — 1 DELIVERED to JPL, initial tests promising
  - 15 ZrC coated FEACs from SRI: — Test samples made, rest in progress
  - 10 single tip FEACs — Fabricated, on hold pending NRL funding

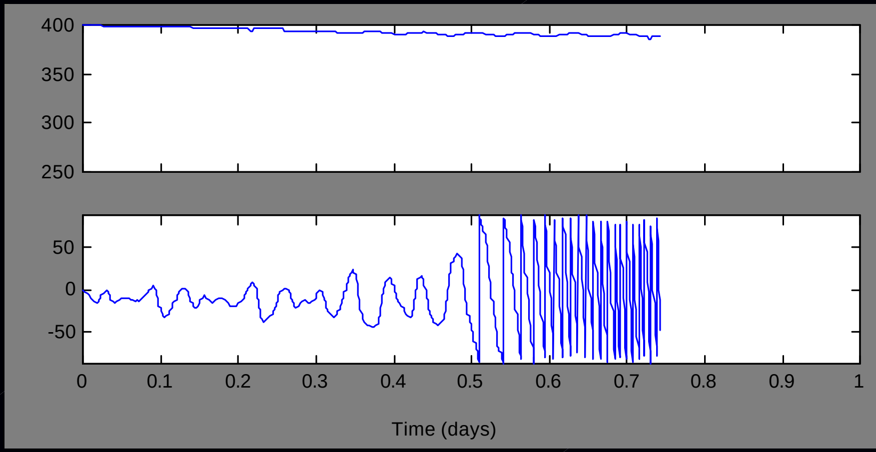
FEAC Testing: Preliminary Results

JPL

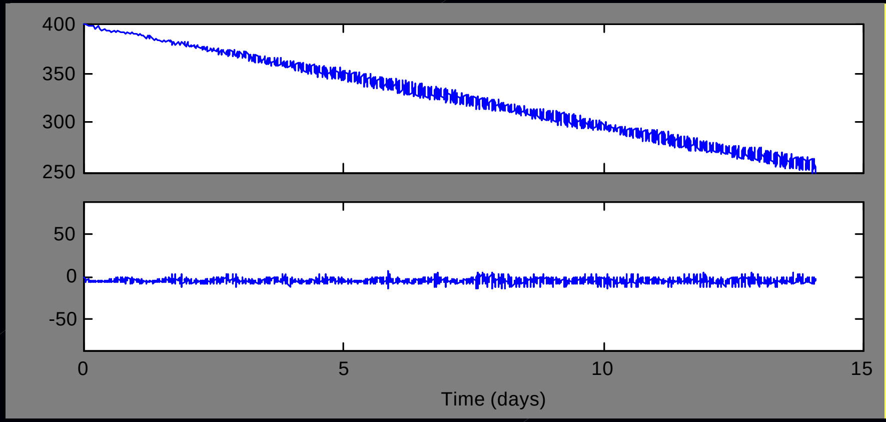
- **Molybdenum cathode**
  - Can operate at 90V and 400uA in 10^{-8} Torr of oxygen for 1 h without permanent damage
  - Cathode performance may be slightly affected by exposure to oxygen environment without electron emission
- **ZrC Coated Molybdenum Cathode**
  - Cathode performance quickly stabilized in UHV environment
  - Cathode performance only temporarily affected by exposure to 10^{-7} Torr of oxygen for 1 hour at 50 V and 200 uA
- **Performance Comparison**
  - Carbide cathode demonstrated significantly improved stability and lower operating voltage in UHV than Mo cathode
  - Carbide cathode was less affected by exposure to oxygen with no electron emission

Tether Dynamics Stabilization

- At low altitude, currents become large enough that tether dynamics are a concern
- ProSEDS will use long ballast tether and heavy endmass to slow instability growth
  - Not a suitable solution for commercial applications
- TT™ Tether Control Unit will monitor endmass dynamics and perform feedback control on tether current to keep tether librations under control



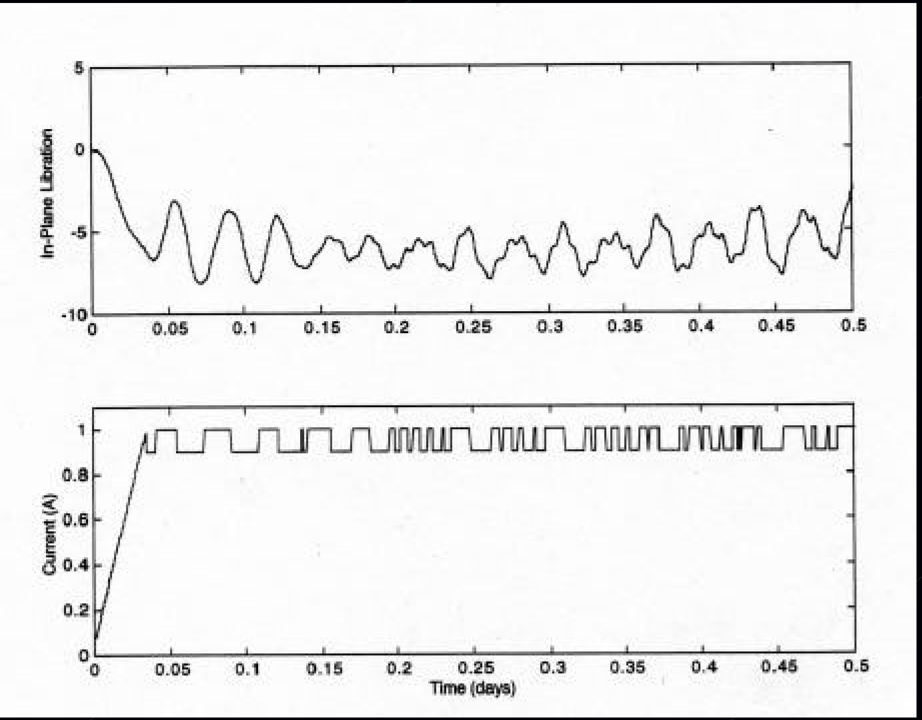
No Control



With Feedback Control

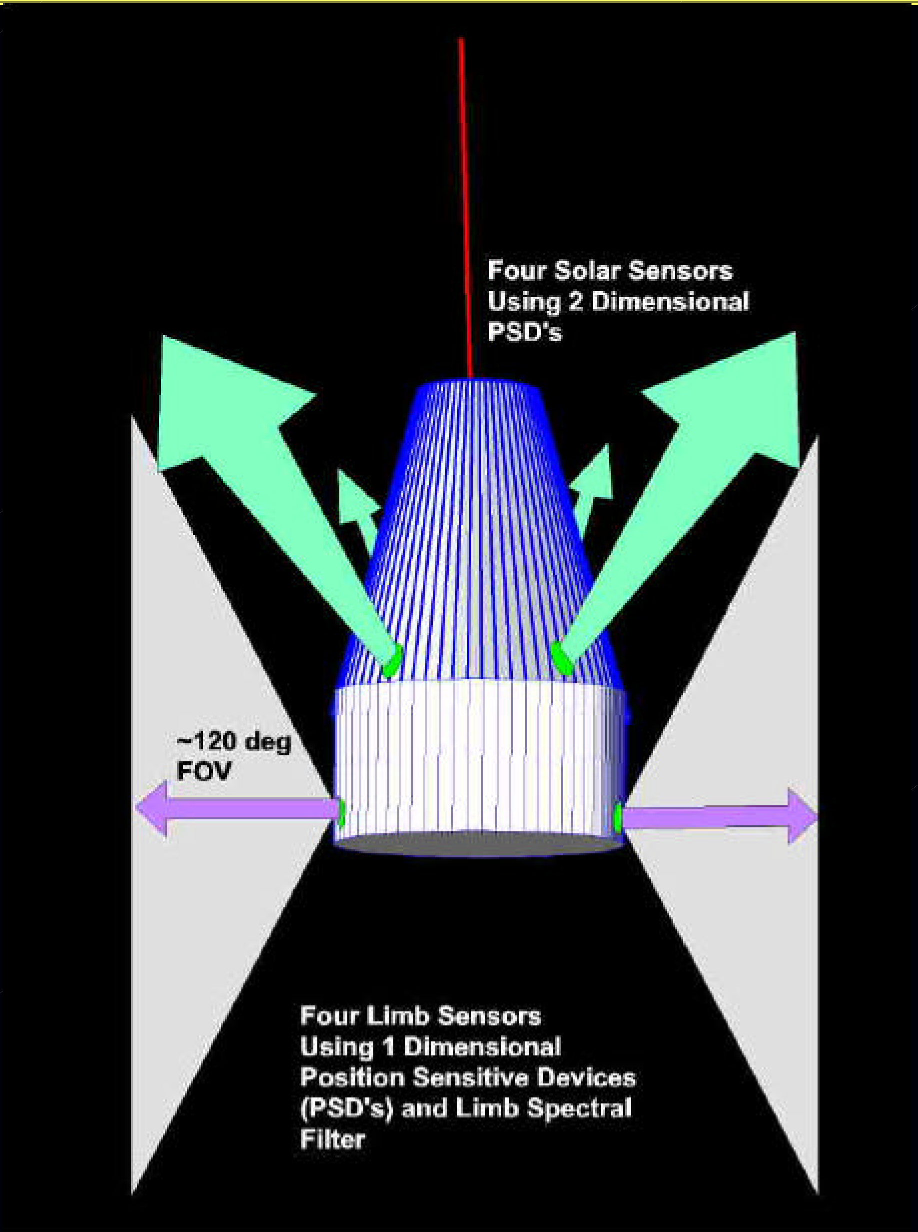
Feedback Method for Stabilization of Tether Dynamics

- Objective is to stabilize tether dynamics with minimum cost, mass, & complexity
- Simulations indicate that feedback damping of In-Plane Libration is most effective
- TCU reduces FEAC current 10% when tether moving backwards
  - Tether stability major objective
  - Detailed control not attempted
- US Patent awarded 9/12/00
  - Other patents in progress
- Feedback method only requires knowledge of whether tether is swinging forwards or backwards



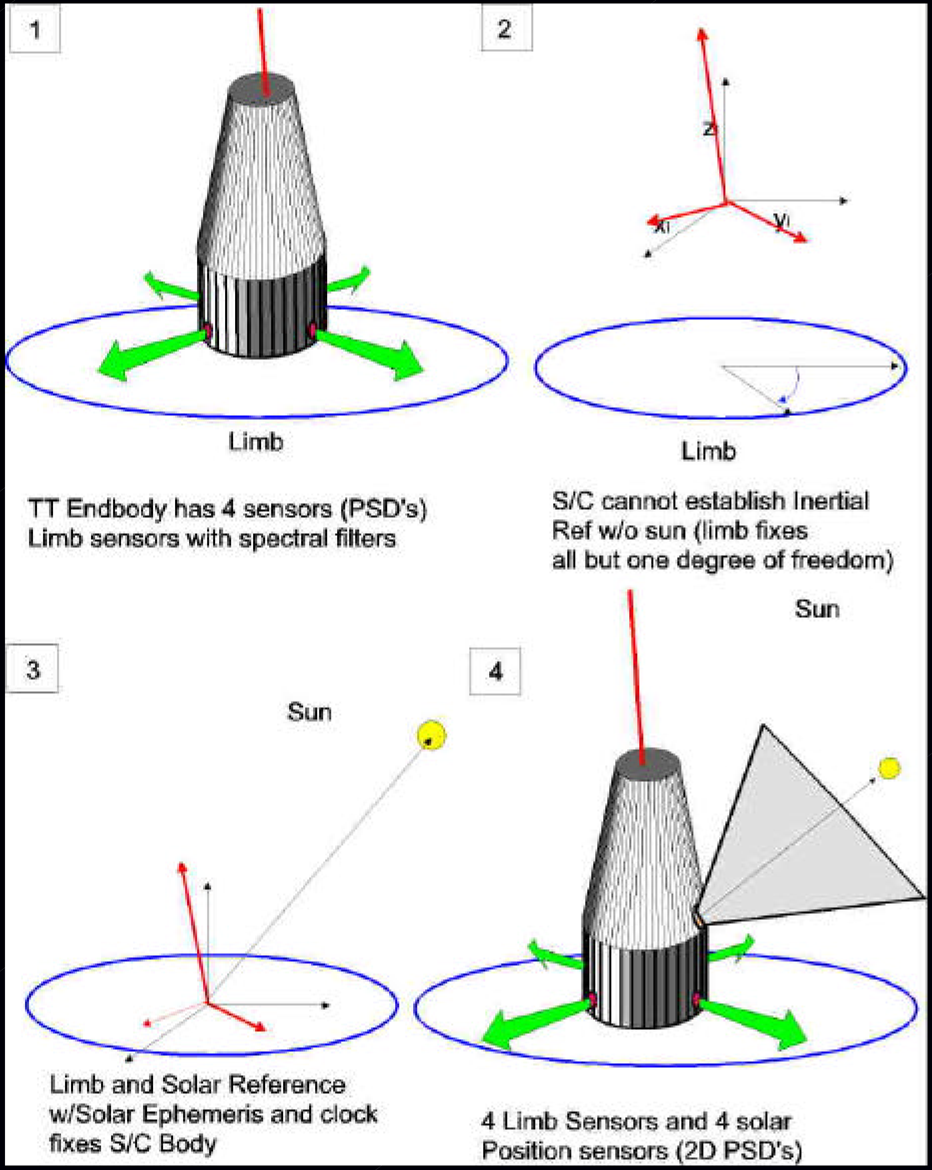
Tether Endbody Attitude Sensing

- Passive observer system
- Utilizes COTS Position Sensitive Devices (PSD)
- Small apertures (~2-3 cm)
- PSD amplifiers previously developed for MSFC
- Sensor redundancy
- High tolerance of large libration angles

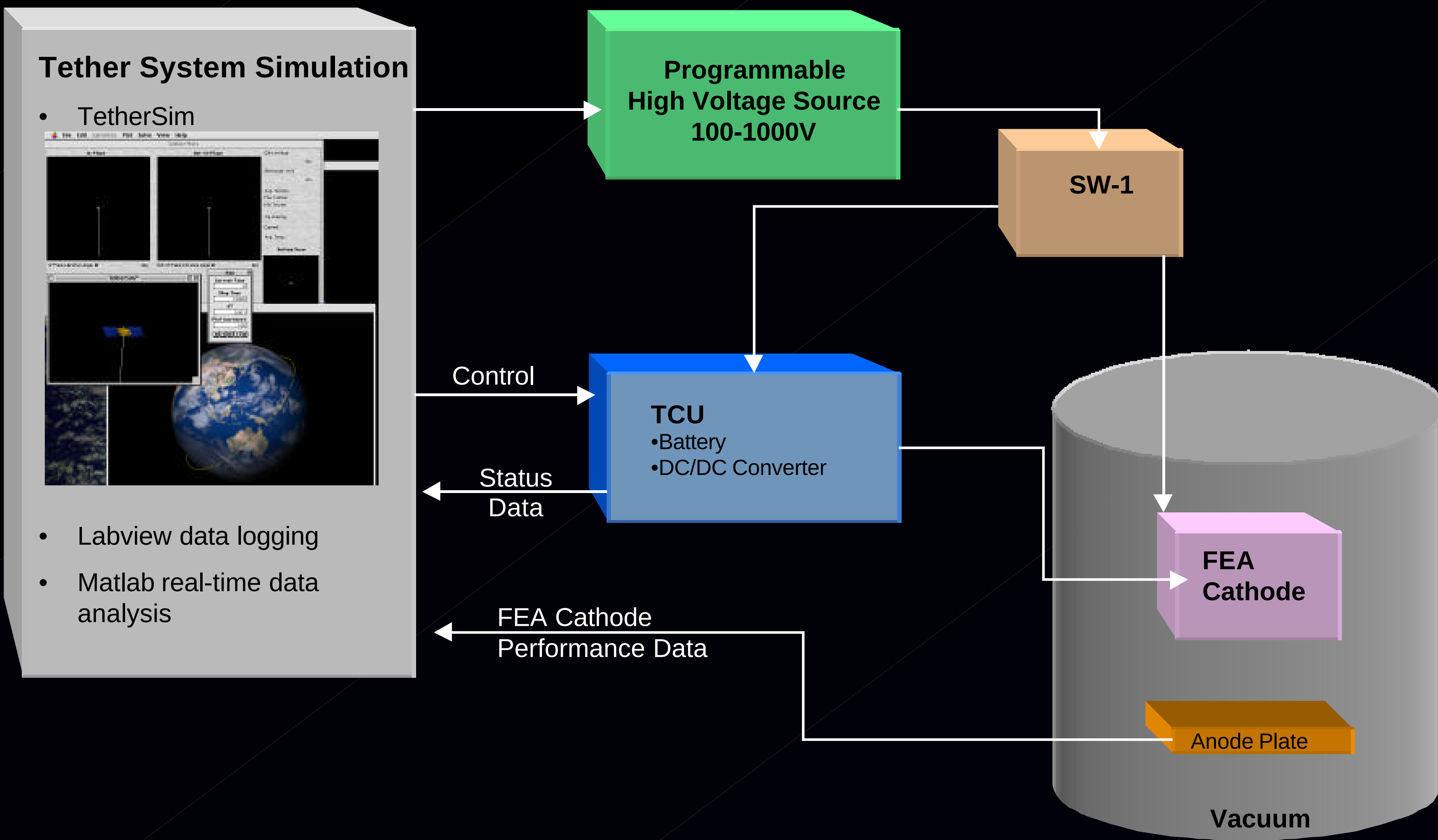


Terminator Tether™ Dynamics Sensing & Feedback

- 4 Earth limb sensors establish deployer endbody pitch and yaw
- 4 Sun/Moon sensors establish endbody roll
- Extended Kalman filter used to determine endbody roll and wobble
- Estimates tether In-Plane and Out-of-Plane librations
- TCU reduces FEAC output by 10% when tether is swinging backwards



Envisioned Phase III Effort:
ED Tether Hardware-In-Loop Testbed



HardWare-In-the-Loop (HWIL) Testing

- HWIL integrates TetherSim™ with hardware for testing electrodynamic tether systems
- Enables real-time and accelerated-time testing of full tether dynamics control methods
- HWIL can be developed in stages:
  - Sensor section
  - TCU section
  - Telemetry section
- Low cost HWIL infrastructure:
  - Programmable power supply
  - Servo-controlled resistor

Business Summary

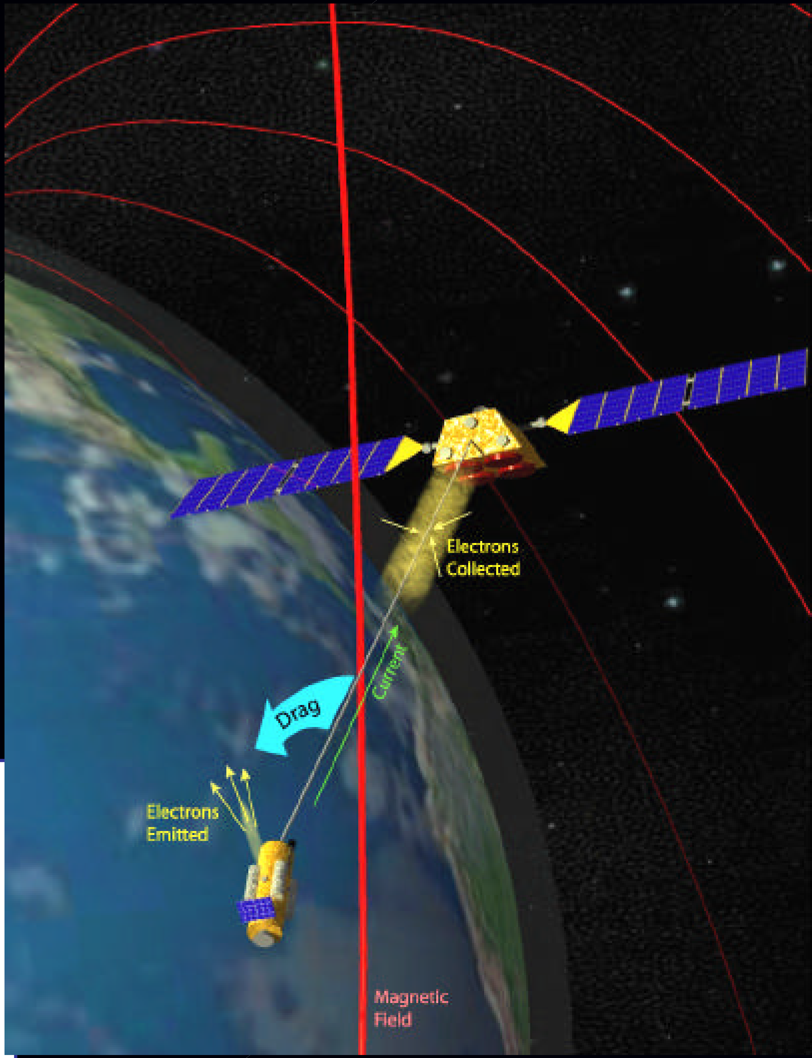
- **Early '99: Marketed TT to Teledesic, Iridium, SkyBridge, LEO One, ECCO, Boeing, Motorola, others**
  - **Strong customer interest**
  - **Customers want flight validation before commitment**
  - **TUI was in negotiations with debis GMBH (DaimlerChrysler Financial arm) for venture capital investment**
- **Aug '99: Iridium Bankruptcy**
- **Apr '00: LEO satellite market becomes uncertain**
- **Present: Need for reliable, cost-effective, autonomous satellite disposal technology <u>still exists</u>**
  - **Recent inquiries from AFRL, Spectrum Astro, Boeing**
  - **Business plan doesn't close for TT developed solely with private investment**

⇨ **<u>Needs Further Government Investment</u>**

Planned 2004 Post-Mission Deorbit of XSS-11 and Target Spacecraft

Demonstration of Post-Mission Satellite Deorbit Using Propellantless Electrodynamic Tether Propulsion

- XSS carries small Terminator Tether™ device
- TT™ inactive during primary XSS-11 mission
- After primary mission completed, XSS-11 “grapples” target satellite and deploys TT™
- TT™ drags against Earth’s magnetic field
- XSS & Satellite lowered to 200 km in months
- Operational vehicle plus tether mass < 50 kg
  - Can be launched from high-altitude jet
  - “On-demand” space debris disposal



Mission Applications™:
- Post-mission deorbit for debris mitigation
- Non-debris-generating method of disposal of unwanted satellite

Terminator Tether™:
- Tether Length: 2-5 km
- Tether Mass: 1-15 kg (depends on target mass)
- Total device mass: 5 to 25 kg
- No propellant required
- No input power required